# Infra-red sub-wavelength imaging

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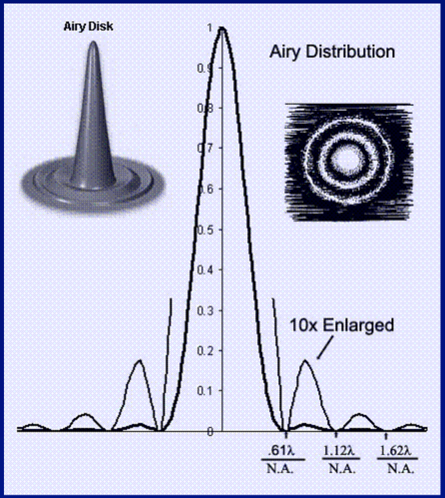
# Optical sub-wavelength imaging

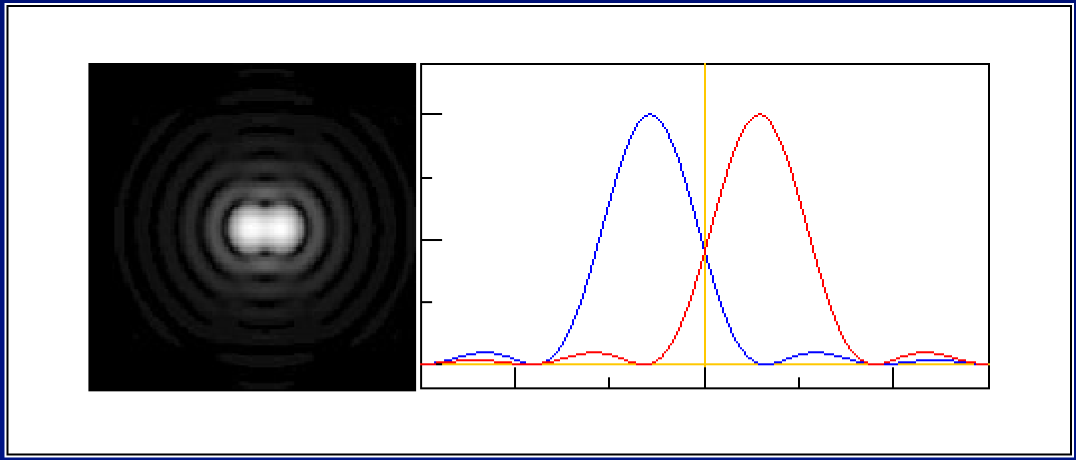
- **Backside optical techniques are critical to fault isolation and logic diagnostics on modern CMOS circuits.**

- **Backside optical resolution is limited by the wavelength of infra-red light.**

- **How can we "beat the resolution limit?"**

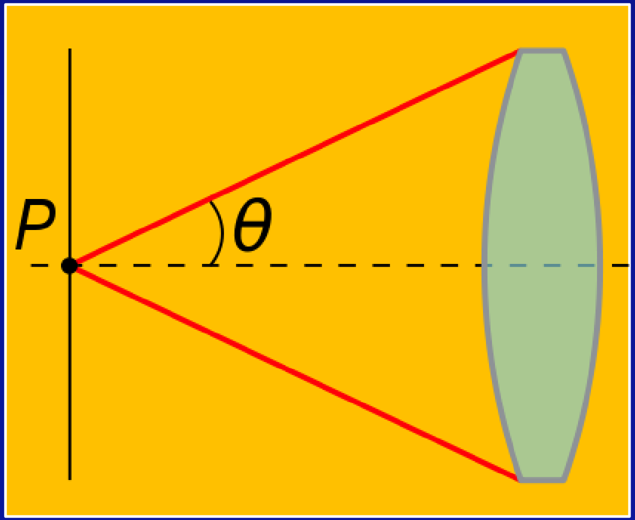
# Rayleigh Criterion



R = Resolution = 0.61 λ / N.A.
N.A. = numerical aperture = n sin θ

Where:
λ = wavelength of light
n = refractive index of the medium the lens is operating in (n = 1 for air).
sin θ $\leq$ 0.95



# Rayleigh Criterion

**For backside work, silicon is transparent above about 1 $\mu$m (1000 nm)**

**If:**
**$\lambda$ = 1064 nm**
**n = 1 (air)**
**sin $\theta$ ~ 0.95**

**Then Resolution $R = 0.61 \lambda / n \sin \theta$ = 680 nm**

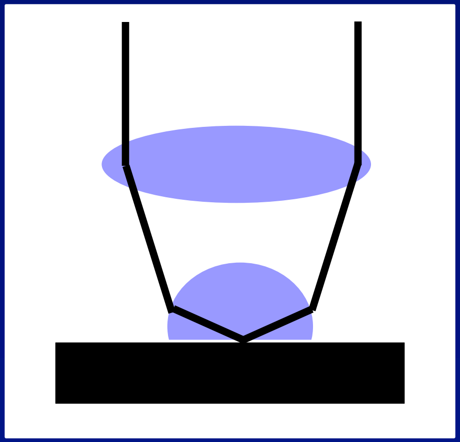
**Note: For FI and debug we don't need resolution equal to the technology node.**

# Solid Immersion Lens

Refractive index of silicon is n=3.6

SIL Improves NA by 3.6

Resolution = 1000 nm * 0.61 / 3.6 * 0.95
= 180 nm



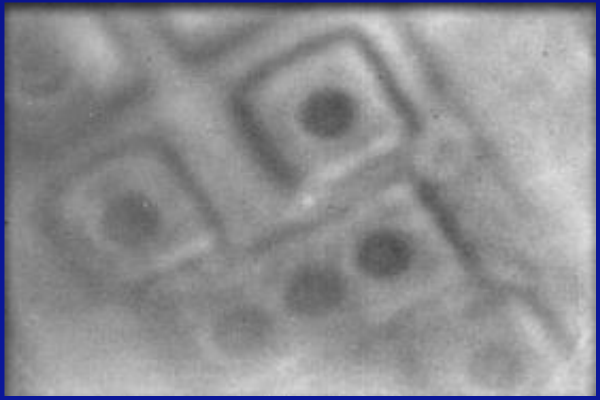
Lens

SIL

Si Chip

Without SIL

With SIL



Images with 100x objective 2 μm

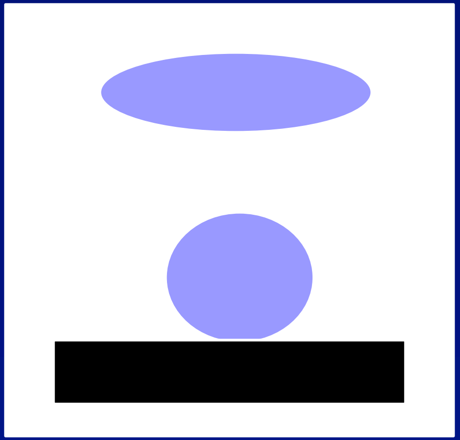
# Solid Immersion Lens

**3.6x is a HUGE improvement in resolution.**

**Relatively inexpensive and easy to use.**

**Can be used for photons in (laser probing) and photons out (photo emission).**

# SIL Improvements?



**1. Weierstrass SIL (Super-hemispherical SIL)**
**N.A. ~ $n^2$**
**- However, N.A. = numerical aperture = n sin θ cannot exceed N.A. = n.**

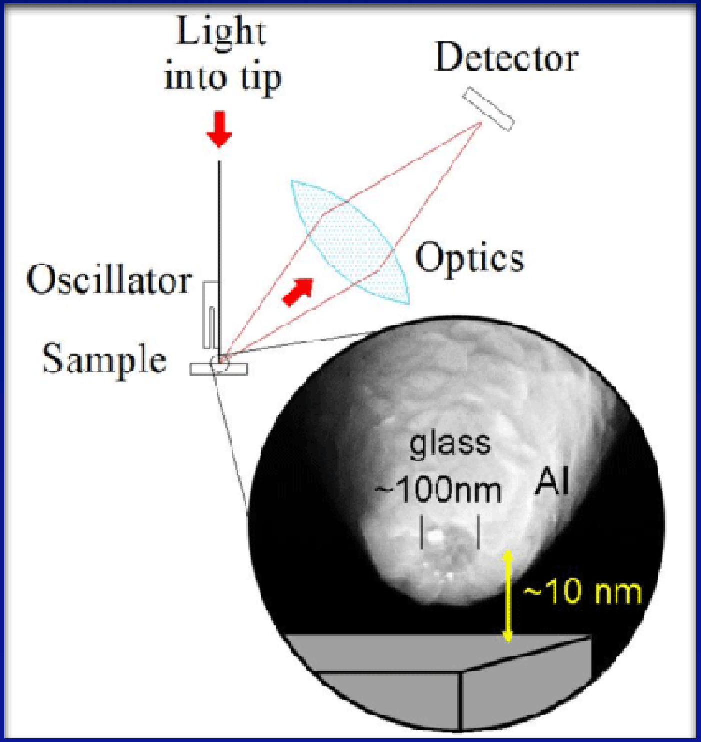
**2. Choose SIL material with N > 3.6?**
**- Best SIL has same index as the substrate material.**

**3. Other ideas?**

# Near-Field Scanning Optical Microscopy

Rayleigh Criteria does not apply in the near field, i.e. within ~ $\lambda$ of the object.

Technology:
- Nominal resolution = 50 nm
- Can be used for photons in (laser probing) and photons out (photo emission).
- NSOM / photo-emission proven (Isakov et al., ISTFA 2008)




Challenges:
- Cannot be combined with SIL
- Scanned technique – slow to collect large image
- Limited signal collection
- Must be very close - sample preparation issue

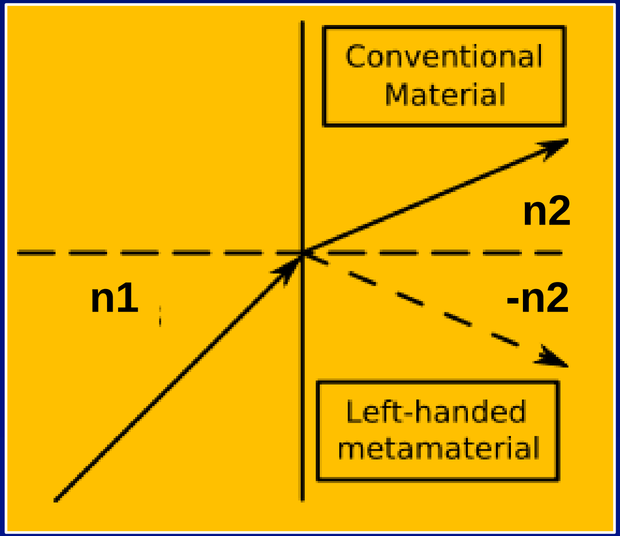
**Note: silicon < 100 nm thick is transparent to shorter $\lambda$**

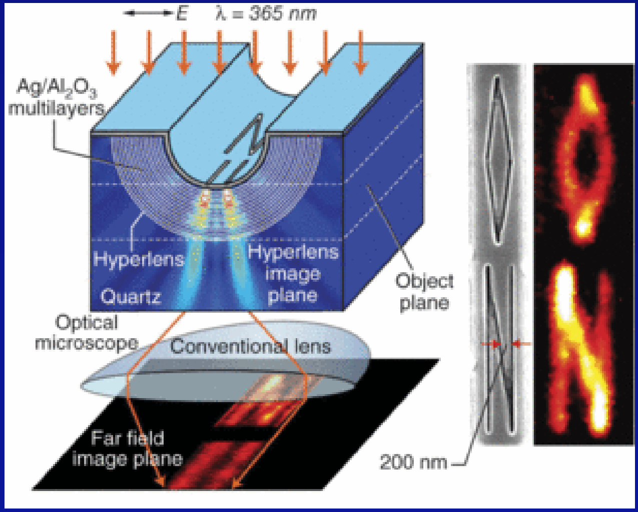
# Meta-Material hyper-lens

**Negative index materials (n<0)**
**"negative refraction"**
**"cloak of invisibility"**

**Technology:**
- **Sub-wavelength imaging demonstrated**
- **Can be used for photons in (laser probing) and photons out (photo emission).**

**Challenges:**
- **Demonstrated resolution is limited**
- **Cannot be combined with SIL**
- **Must be very close - sample preparation issue**




**Zhang, et al., UC Berkeley**

# Point Spread Function Fitting

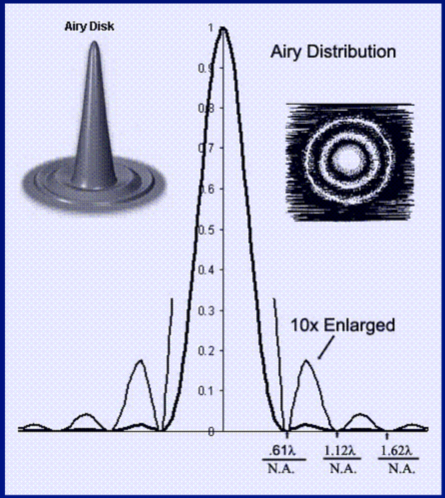
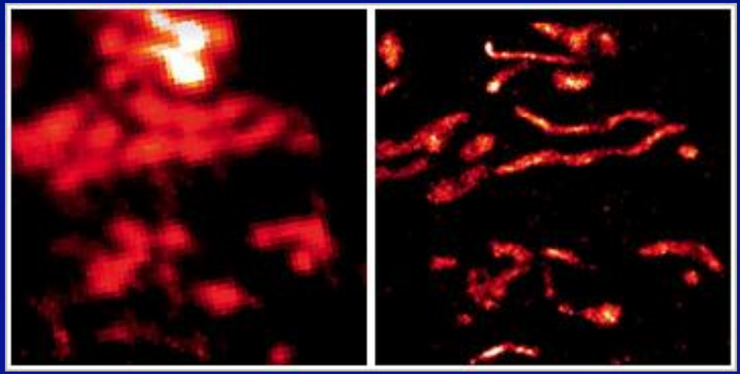



Photo-activated localization microscopy (PALM) or Stochastic optical reconstruction microscopy (STORM)
Sparsely populated point sources can be localized by curve fitting routines.

Technology:
- 20 nm resolution demonstrated (biological samples).
- May be combined with SIL



Eric Betzig, et al., Howard Hughes Medical Institute

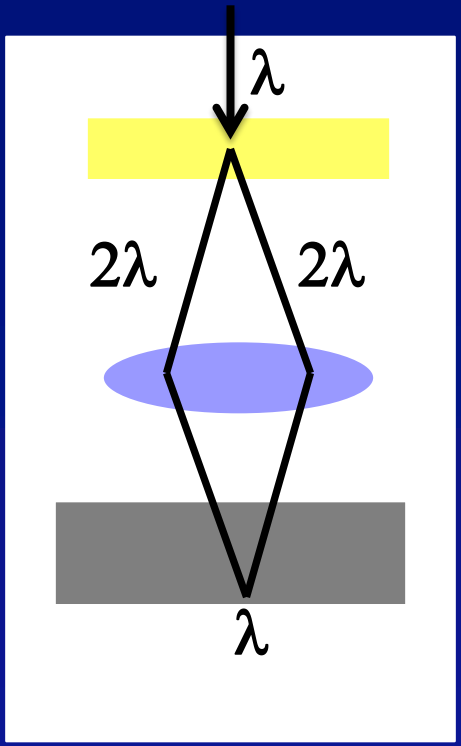
Challenges:
- Cannot be used for photons in (laser probing)
- Requires a lot of photons
- CMOS photo emitters may not be sparsely populated

# Entangled Photon Imaging

**"Entangled photons" can be recombined to form one photon with half the wavelength**

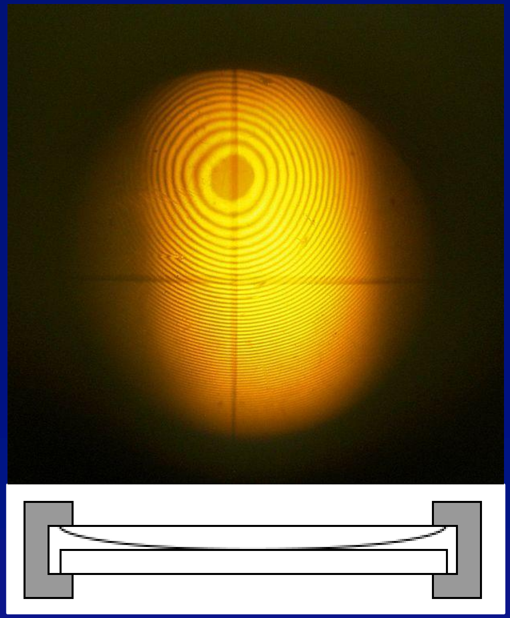
**Technology:**
- **N = 2 gives 2x better resolution**
- **N = 4 gives 4x better resolution, etc.**
- **May be combined with SIL**

**Challenges:**
- **Little experimental data**
- **Cannot be used for photons out (photo emission)**
- **Entangled photon sources only a few % efficient**



# Interference Microscopy

Interference Microscope splits and recombined a beam to form an interference pattern.
Can measure Z step height differences on thin films with 1 Å precision
(X and Y precision much poorer, ~$\lambda$)



Newton's Rings

**Technology:**
- Various sources claim that the technique can be generalized to 3-D

**Challenges:**
- Little experimental data
- Metrology tool, not useful for photo emission or laser probing